Towards optimization of a real-world Robotic-Sensor System of Systems

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ABSTRACT

The problem of threat detection in an unstructured environment is considered. Three systems, comprising of robots and sensors, are proposed to form a system of systems (SoS) to find a solution to the problem. System interactions are defined to provide a framework for formulation as an SoS optimization problem. Different cost and objective functions are introduced for optimization of local criteria. Using different weights, a linear combination of the local cost and objective functions is obtained to propose a global objective function. An algorithm is suggested to find an optimum value for the global objective function leading towards optimization of the SoS.

KEYWORDS: Systems of Systems, Robotic Swarm, Sensor Network, Optimization.

1. INTRODUCTION

Recently there has been a strong focus on new System of Systems (SoS) concepts and strategies [1]. The need for performance optimization among group of heterogeneous systems in order to realize a common objective is becoming the focus of a diverse range of applications including military, security, aerospace and disaster management [2,3]. There is an increasing need to achieve synergy between these independent systems in order to achieve desired overall system performance. Recently researchers have addressed the issue of coordination and interoperability in system of systems [4,5].

The concept of SoS arises from the need to more effectively implement and analyze large, complex, independent, heterogeneous systems working cooperatively. The SoS paradigm presents a new school of thought in Systems Engineering. The driving force behind the desire to view these systems as an SoS is to achieve higher capabilities and performance than would be possible with a traditional stand-alone system. The SoS concept presents a high-level viewpoint and allows understanding of the interactions between each of the independent systems. The SoS concept however is still at its developing stages [6,7].

The literature has revealed that much of this recent work introduces new concepts towards an SoS approach. However, very few researchers have attempted application to real-world scenarios [4]. This paper presents an approach towards optimization for our case study utilizing the SoS philosophy.

The case study presented in this paper includes various robotic systems with varying degrees of autonomy as well as a network of sensing devices. There have been several research studies focusing on sensor network and power optimization [8-10]; however, very few address the problem of optimization when sensor networks work cooperatively with other systems.

In this paper an optimization problem is considered for a system consisting of a sensor network and mobile robots. The task of this SoS is to detect a threat in an unknown environment. The systems proposed to accomplish this task are a *master robot,* a *sensor network and a swarm of robots.* An optimization problem is then formulated for the SoS, subject to the limitations imposed by each of these systems.

This paper is organized as follows. Section 2 provides the problem statement and describes each of the individual systems in detail. In section 3 the SoS optimization problem is formulated and strategies to solve this problem are suggested. The concluding remarks are included in section 4.

2. PROBLEM STATEMENT

In this paper we propose a system of robots and sensors to solve the problem of *security monitoring* in an unknown hazardous environment. We consider three systems varying in their operational behavior cooperating in order to perform security monitoring of the desired area. These systems are the semi-autonomous controlled master robot, autonomous robotic swarm and autonomous network of sensors. These operationally independent systems are required to work together to achieve the desired task and by their nature form a System of Systems. The overall system architecture is shown Figure 1.

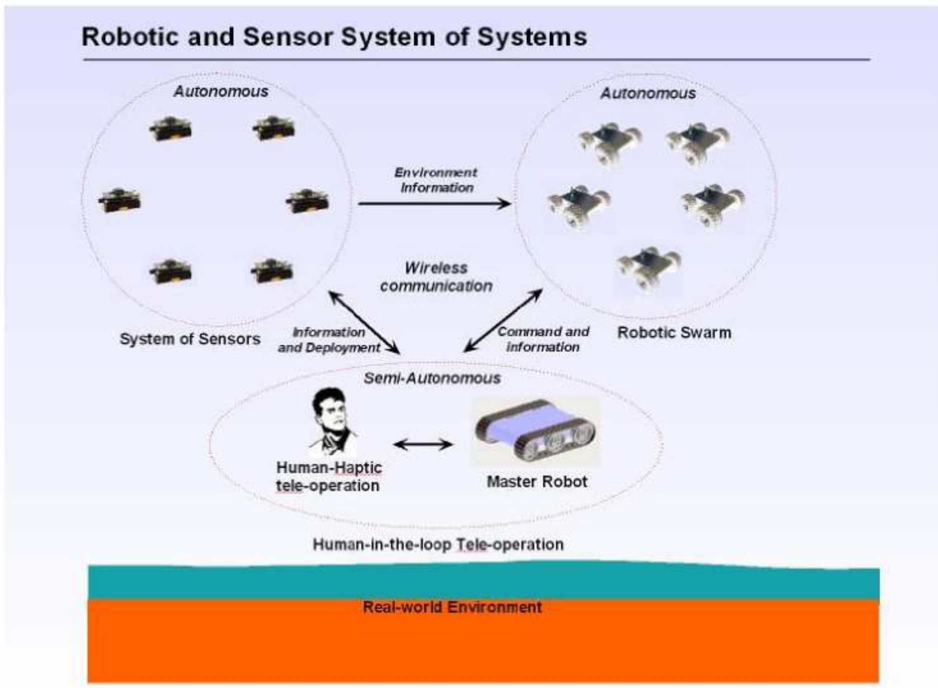

Figure 1. System of Systems Architecture

The master robot is responsible for exploration of the entire unknown area and utilizes human control for intelligent maneuvering in harsh and cluttered environments so as to maximize the area monitored. The human-in-the-loop control enables evaluation of the area to be completed with human level judgement and intuition. This robot is also responsible for physical deployment of sensor nodes at the discretion of the autonomous sensor network. The fraction of the total area traversed determines the *degree of coverage* as a performance metric for this system. Since sensor nodes are dropped by the master robot, their placement is constrained to the areas physically visited by this system. A better distribution of the sensor network is achieved if master robot attains an acceptable degree of coverage. The nodes lend themselves to be densely deployed forming a deeply embedded network. Multiple sensors can be used collaboratively to monitor events or space more effectively than a single sensor. These sensor nodes are very cost effective. They are however low powered and have low computation and communication capabilities. Therefore, in order to achieve adequate sensory coverage for any application, consideration of placement and density are vital. Once deployed, each sensor node can sense the environment within a circular region centered at the location of the sensor and with a radius r. The overall coverage is the union of areas covered by the active sensor at each time sample. The autonomous robotic swarm is dispatched by the sensor network after a threat is detected. The role of the robotic swarm in this application scenario is to locate the threat with a better precision and possibly eliminate the threat. The swarm of robots are provided with sensory information of environment from the sensor network. This information is used for assistance in localization, navigation, etc. Therefore, the

effectiveness of the sensor network in sensing its surrounding area has a direct impact on the performance of the robotic swarm.

3. SYSTEM OF SYSTEMS OPTIMIZATION

In this section, we present an approach to optimization for an SoS performing the security monitoring of a dynamic environment using the above described combination of robotic and sensor systems. In order to formulate our optimization problem we need to define the performance metrics and constraints for each of the systems. We explain how the requirements for different systems can be conflicting and how the SoS problem can be solved.

Master Robot

In this particular surveillance scenario, the master robot performs the assessment of the entire area to be monitored. The objective is to cover as much of the target area as possible. The performance metric for the master robot is the degree of coverage, ρ_c, defined as:

$$\rho_c = \frac{A_C}{A_T} \tag{1}$$

where A_T is the total area required to be covered and A_C is the area actually covered by the master robot. The difference between these two values represents the areas in which the robot cannot physically navigate, e.g. presence of obstacles, rough terrain etc. According to this definition: $0 \le \rho_c \le 1$, *i.e.* ρ_c=0 and ρ_c=1, indicate zero and total coverage, respectively. As explained above, in order to better deploy the sensor network, a better degree of coverage (ρ_c) is desired. This requirement however is sometimes challenged by the presence of rough terrain which exposes the master robot to danger. Therefore, the safety issue of the master robot imposes a constraint on the degree of coverage. This constraint can be given by the following inequality:

$$\rho_c \le \rho_{th} \tag{2}$$

where ρ_{th} represents a threshold imposed by the operator to ensure survivability of the robot. If this threshold is increased the robot can discover more of the area, however, it is more exposed to risk.

Sensor Network

In the previous section we considered the master robot's limitation in covering the entire area of interest, which has a direct impact on the deployment of the sensor network. The sensor network's objective is to cover as much of the target area as possible. Let us assume that n_d is the desired number of sensor nodes in the area of interest. Since master robot cannot cover the whole area, the number of sensor nodes that will be deployed will decrease to n, given by:

$$n=[n_d . \rho_c] \tag{3}$$

where the square brackets denote the integer portion of the contents. The problem becomes optimization of the performance of this sensor network subject to the constraints imposed by other systems.

An important consideration when dealing with sensor networks is power consumption. There are numerous ways to sustain the lifetime of the sensor network. Three solutions to confront this problem are considered in this paper.

1) *Switching to redundant nodes*: During the deployment of the sensors, the master robot can place redundant sensors in the environment. These redundant nodes act as back-up nodes and can take over the task of sensing and signal communication from any dying nodes in order to sustain overall network lifetime. If we assume that n is the number of times or locations that the master robot drops the sensors and n_i is the

number of sensors (redundant and non-redundant) at location *i*, then the total number of sensors *m*, can be obtained by:

$$m = \sum_{i=1}^{n} n_i \tag{4}$$

The deployment of redundant sensors imposes the following cost function:

$$J_r = cm \tag{5}$$

where *c* is assumed to be the fixed cost for each sensor. Hence J_r will be the cost of having this set of *m* sensors (redundant and non-redundant) and is subject to the maximum acceptable cost. Therefore, the number of sensors is constrained by the following condition:

$$m \le \frac{b}{c} \tag{6}$$

where *b* is the maximum acceptable cost for the sensors.

2) *Time scheduling:* Another way to save battery power is to schedule the sensors to sense the environment at different samples or intervals of time. In this case some information might be lost. However, if there is only one sensor at a particular location, the option of switching to another sensor does not exist and sampling could be useful. Figure 2 shows how each sensor is switched on and off to save power. In this figure T_{on} is the activity period for a sensor.

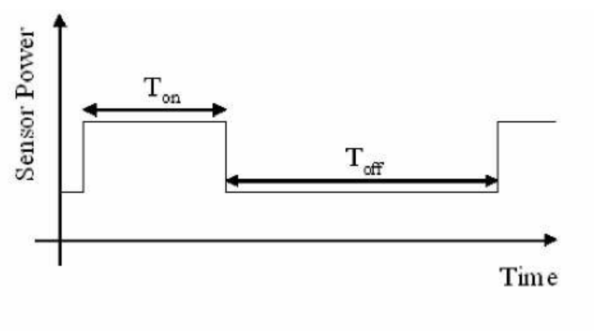

Figure 2. Time scheduling for a typical sensor

For each sensor we define a *scheduling parameter*, γ, given by:

$$\gamma = \frac{T_{on}}{T_{on} + T_{off}} \qquad (0 \le \gamma \le 1) \tag{7}$$

This parameter is considered as a criterion to determine how active each sensor is. We now obtain a cost function related to this power saving strategy. The cost function, J_s, can be considered as:

$$J_s = \frac{1}{m} \sum_{i=1}^{m} \gamma_i \qquad (0 \le J_s \le 1) \tag{8}$$

where γ_i, $i = 1,2,\ldots m$ is the scheduling parameter for sensor *i*. A low value of J_s implies that more power is being conserved. However, if J_s is decreased more information from the environment is likely to be lost. A low J_s may also impose certain navigational constraints for the swarm of robots. Therefore, minimization

of the cost function J_s is subject to having an acceptable performance degradation in guiding the robotic swarm and detecting the threats. Let us define Γ as a vector comprising of all scheduling parameters corresponding to each sensor. This vector can be expressed as:

$$\Gamma = [\gamma_1, \gamma_2, \ldots, \gamma_m] \tag{9}$$

Let us also assume $\Gamma_{\min}$ is a vector comprising of scheduling parameters which satisfy swarm navigation and threat detection requirements. This vector can be given by:

$$\Gamma_{\min} = [\gamma_{1\min}, \gamma_{2\min}, \ldots, \gamma_{m\min}] \tag{10}$$

The cost function J_s can now be re-written as:

$$J_s = \frac{\|\Gamma\|_1}{m} \tag{11}$$

where $\|\,.\,\|_1$ is the L_1 –norm [11]. It becomes obvious that this cost function is minimized when $\|\Gamma\|_1$ is minimized. However, the swarm navigation and threat detection requirements impose the following constraint:

$$\|\Gamma\|_1 \geq \|\Gamma_{\min}\|_1 \tag{12}$$

3) *Power reduction*: This strategy is the last method that we have considered to conserve power. In this approach the power at which each sensor is operating is decreased to a portion of the full power. This reduces the area of coverage of each sensor. However, it could be considered as another method to preserve battery power. A *power reduction parameter*, λ, is defined as below to determine the operational power for each sensor:

$$\lambda = \frac{P_a}{P_f} \qquad (0 \leq \lambda \leq 1) \tag{13}$$

where P_a is the actual operating power and P_f is the full power for each sensor. The cost function, J_P, for the overall sensor network can be defined as:

$$J_p = \frac{1}{m}\sum_{i=1}^{m} \lambda_i \qquad (0 \leq J_p \leq 1) \tag{14}$$

where λ_i, $i = 1,2,\ldots m$ is the power reduction parameter for sensor *i*. Similar to the previous strategy, the operational power has to satisfy a minimum value in order to detect the hazards and guide the swarm robots effectively. Let us define the vector of power reduction parameters for all sensors as:

$$\Lambda = [\lambda_1, \lambda_2, \ldots, \lambda_m] \tag{15}$$

Let us also assume $\Lambda_{\min}$ is a vector comprising of power reduction parameters which satisfy swarm navigation and threat detection requirements. This vector can be expressed as:

$$\Lambda_{\min} = [\lambda_{1\min}, \lambda_{2\min}, \ldots, \lambda_{m\min}] \tag{16}$$

The cost function J_p can now be written as:

$$J_p = \frac{\|\Lambda\|_1}{m} \tag{17}$$

This cost function is minimized when $\|\Lambda\|_1$ is minimized. However, the swarm navigation and threat detection requirements impose the following constraint:

$$\|\Lambda\|_1 \geq \|\Lambda_{\min}\|_1 \tag{18}$$

All the above mentioned strategies help minimize power consumption in the sensor network. We now consider the problem of maximizing the area of coverage while consuming minimum power. The total area covered by the sensors, a_{cT}, is given by:

$$a_{cT} = \bigcup_{i=1}^{m} a_{ci} \tag{19}$$

where a_{ci} is the area covered by sensor i and $\bigcup$ represents the union operation on the areas. As was mentioned earlier, the total area of coverage is subject to the degree of coverage by the master robot, ρ_c. Therefore, a_{cT} can be increased if the operator increases the threshold, ρ_{th}, in the inequality (2). The objective function, J_a, for the area covered by the sensors can be introduced as:

$$J_a = \frac{s(a_{cT})}{s(A_T)} \tag{20}$$

where s is an operator generating the surface area of its argument. If there is negligible or no overlapping between the areas associated to individual sensors, this objective function can be estimated as:

$$J_a = \frac{s(a_{cT})}{s(A_T)} = \frac{s(\bigcup_{i=1}^{m} a_{ci})}{s(A_T)} \cong \frac{\sum_{i=1}^{m} s(a_{ci})}{s(A_T)} \tag{21}$$

For simplicity it can be assumed that there will be no redundant sensors in the sensor network. Therefore, we can form the overall objective function, R, to be maximized as:

$$R = w^T \cdot J = [w_1 \ w_2 \ w_3] \begin{bmatrix} J_a \\ -J_r \\ -J_p \end{bmatrix} = w_1 J_a - w_2 J_r - w_3 J_p \tag{22}$$

where w is the weight vector, J is the vector composed of local cost and objective functions and w_1, w_2, w_3 are non-negative weights associated to each objective reflecting its importance and should be chosen dynamically. Hence the optimization problem can be formulated as:

$$\begin{aligned} &\textit{maximize:} && R(\Gamma, \Lambda, \rho_c) \\ &\textit{subject to:} && \|\Gamma\|_1 \geq \|\Gamma_{\min}\|_1 \\ & && \|\Lambda\|_1 \geq \|\Lambda_{\min}\|_1 \\ & && \rho_c \leq \rho_{th} \end{aligned} \tag{23}$$

In other words, the desired Γ, Λ and ρ_c should be found to maximize the overall objective function and satisfy the constraints due to master robot safety, swarm navigation and threat detection requirements. The threat detection constraint imposes a minimum scheduling and power reduction parameter (γ and λ) for each sensor. However,

since swarm robots are mobile, the problem of determining the optimum power reduction and time scheduling parameters for each sensor becomes more of a dynamic problem which will be discussed in the following subsection.

Swarm of Robots

In order to find the optimum objective function, swarm mobility should be considered. All the sensors initially maintain the desired values for scheduling and power reduction parameters (γ and λ) obtained from the threat detection constraint. This constraint can be assumed a weaker constraint than the one imposed by the swarm robots as long as the sensors are only monitoring the area and no threat has been detected. When a threat is detected by a sensor, the swarm of robots are dispatched to the area of threat. We assume that the swarm of robots need the assistance of the sensor network to navigate through area and to find their relative location with respect to the area of threat. Therefore, after detection of a threat by the sensor network, the distance between each individual swarm and sensor is evaluated. The closest sensor to each robot is then located. Next the scheduling parameter for the sensors in vicinity of each robot should be increased to a value required for swarm navigation. The parameters associated to other sensors are not changed. However, all parameters should be updated dynamically because of the robotic swarms mobility. The rate at which these parameters should be updated depends on the speed of the swarm of robots. After a robot moves closer to another sensor the parameters are updated for the new neighboring sensor in the same fashion. Utilizing this method keeps all sensors operating at a minimum power. At the same time the swarm of robots are guided through the sensor network to reach the area of threat.

4. CONCLUSIONS AND FUTURE WORK

In this paper we have considered mobile robots operating together with a sensor network as a System of Systems (SoS) to conquer the problem of detection and isolation of threat in an environment. The problem was then formulated as an SoS problem. Many recent papers have suggested different structures and modeling for SoS. However, very few have discussed how these modeling and optimization techniques can be formulated for real-world examples of System of Systems. In the case study, discussed in this paper, we proposed three systems; namely the master robot, sensor network and robotic swarm. The limitations of each system were described. A global objective function was then developed according to the interactions between the different systems and their limitations. The formulation and SoS methodology used in this paper can be modified to suit a large class of System of Systems.

Figure 3. Research platform under development

The focus of the optimization problem in this paper has been a sensor network interacting with a group of robots. Many authors have attempted to address the problem of power saving in sensor networks; however, very few have considered integration with real-world robotic systems. In this paper we have investigated the trade-off between the power consumption in a sensor network and performance degradation of the mobile robots which cooperate with the sensor network. The same analysis and modeling can be applied for sensor networks interacting with a wide range of systems.

The concepts presented in this paper were considered for a specific application of security monitoring of an unstructured environment. The actual master robot, robotic swarm and sensor network are currently under development, as shown in figure 3. The physical realization of these systems will provide a research platform for implementation of the SoS optimization strategies presented in this paper.

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